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Sediment Resuspension Dynamics in Canopy- and Meadow-Forming Submersed Macrophyte Communities

William F. James and John W. Barko

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP) Work Unit Number 33128. The APCRP Program is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, MS. Funding was provided under the Department of the Army Appropriation 96X3122, Construction General. The APCRP is managed under the Center for Aquatic Plant Research and Technology (CAPRT), Dr. John W. Barko, Director. Mr. Robert C. Gunkel, Jr., was Assistant Director, CAPRT. Technical Monitor during the study was Mr. Timothy Toplisek, HQUSACE.

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1 Introduction

Background

Macrophytes play an important positive role in reducing sediment resuspension in shallow lakes and reservoirs by stabilizing the sediment from wind-generated wave activity and resuspension (James and Barko 1990, 1994; Dieter 1990; Barko and James 1998). However, macrophyte dominance can often be disturbed in these systems by a variety of mechanisms (e.g., lake level fluctuations, explosions of benthic fish communities, strong storms or high winds) leading to a changeover to a more turbid, algal-dominated state (Maceina and Soballe 1990; Sheffer 1990; Sheffer et al. 1993; Breukers et al. 1997). Thus, a goal of shallow lake restoration is the promotion and maintenance of stable submersed macrophyte communities for purposes of reducing sediment resuspension, sediment export, and improving water quality (Hosper 1989; Hosper and Jagtman 1990; Hanson and Butler 1990; Jeppesen et al. 1997). Little is known about the effectiveness of canopy-forming (i.e., biomass structure near the lake surface) versus meadow-forming species (i.e., low-growth forms) of macrophytes in dampening wave energy and reducing sediment resuspension. Yet, this information is of importance when making management decisions which influence the maintenance of different macrophyte populations in shallow water systems. We examined the impacts of a macrophyte community's dominated by a canopy-forming (*Myriophyllum sibiricum*) and a meadow-forming (*Chara*) species on sediment resuspension in Lake Christina, Minnesota.

Study Site

Lake Christina is a large (1,620 ha), shallow (mean depth = 1.25 m) glacial lake located in Western Minnesota. The lake currently exhibits an extensive submersed macrophyte community dominated by *Potamogeton pectinatus* and the macroalgae *Chara* sp. *Myriophyllum sibiricum* is also abundant and occurs in nearly monospecific stands, particularly along the northern region of the lake. The lake underwent a biomanipulation consisting of rough fish eradication and restocking with largemouth bass and walleye in 1987 in an effort to reduce bioturbation, increase zooplankton grazing pressure on algae, and stimulate submersed macrophyte growth (Hanson and Butler 1990, 1994).

2 Methods

A station was established in a nearly monospecific stand of *Chara* and an adjacent stand of *M. sibiricum* in the north-central area of the lake for continuous monitoring of *in situ* turbidity (Figure 1). This area of the lake was chosen because water column depths within each macrophyte bed were the same (1.2 m deep). The distance between the two stations was approximately 100 m.

Turbidity was measured 0.25 m above the sediment surface at 15-min intervals at each station using YSI 6000 data sondes equipped with turbidity probes (Model 6026, YSI Incorporated, Yellow Springs, Ohio). The probes were pre- and post-calibrated with standard solutions (range of 0 to 100 NTU) purchased from YSI (YSI 6073, YSI Incorporated, Yellow Springs, Ohio). At approximately biweekly intervals, the data sondes were serviced, cleaned, recalibrated, and redeployed. A continuous record of *in situ* turbidity was obtained at the *Chara* station between 22 July and 23 September 1998. A continuous record of *in situ* turbidity was obtained at the *M. sibiricum* station between 22 July and 31 August 1998. Malfunctioning of the data sonde prevented data collection at this station between 1 and 23 September 1998.

Wind speed and direction (Wescor, Inc. Model 824) were measured at 15-min intervals during the same period at a weather station located near the *M. sibiricum* station. The wind anemometer was located ~2 m above the lake surface. The wave models developed by Carper and Bachmann (1986), Hamilton and Mitchell (1996), and Baily and Hamilton (1997) were used to determine effective fetches and theoretical bottom shear stresses (dynes/cm^2) at the sediment-water interface at the *Chara* and *M. sibiricum* stations using continuous records of wind speed and direction. The theoretical bottom shear stress was calculated as:

$$\tau = H\left[\frac{\rho\left(\nu\,(2\pi\,/\,T)^3\right)^{0.5}}{2\,\sinh\,(2\,kh)}\right]$$

where

τ = bottom shear stress

H = wave height (cm)

ρ = density of water (1 g cm^{-3})

T = wave period (s)

v = kinematic viscosity

k = wave number ($2\pi/L$ where L = wave length, cm)

h = water depth (cm)

Since our calculation does not include the impacts of submersed macrophytes on wave activity and τ, we interprete τ as a theoretical reference shear stress only.

The critical bottom shear stress (τ_c) of sediments in Lake Christina was determined experimentally using a particle entrainment simulator (PES) designed exactly as described by Tsai and Lick (1986). The PES consisted of a vertically oscillating, perforated acrylic grid that was driven by a computer-controlled motor. The grid was positioned so that the bottom of its oscillation cycle occurred exactly 5.08 cm (2 in.) above the interface of an in tact sediment core. A cam on the motor shaft allowed the grid to oscillate up and down for a distance of 2.54 cm (1 in.).

In July, five intact sediment cores, ~ 10 cm in depth, were collected in the vicinity of the *Chara* and *M. sibiricum* stations using a 15- by 15-cm box corer (Wildco Wildlife Supply Co.) for determination of τ_c. The sediment contained in the corer was carefully extruded into a 13-cm (5-in.)-diam by 20-cm acrylic cylinder. In the laboratory, ~ 1.36 L (to a height of 13 cm (5 in.)) of filtered lake water was carefully siphoned onto the sediment surface of the sediment core system before inserting it into the PES.

To determine τ_c, the motor of the PES was programmed to oscillate above the sediment interface in a stepwise manner from 0 to 800 RPM (100 RPM increments) at 10-min intervals. At 8 min into each RPM cycle, a 50-mL sample was collected 2.54 cm below the water surface by using a peristaltic pump. Water removed as a result of sampling was simultaneously replaced with filtered lake water using a peristaltic pump. Samples were analyzed for total suspended sediment (TSS) according to APHA (1992). RPM was converted to τ by using the calibration curve developed by Tsai and Lick (1986) (see Tsai and Lick 1986, Figure 5, page 317) for levels ranging between 430 and 750 RPM. We used linear interpolation to estimate τ for levels that occurred below 450 RPM and above 750 RPM. Thus, τ ranged from 0 to nearly 6 dynes/cm^{-2}. The τ_c was estimated as the inflection point where TSS increased in an exponential pattern.

In the absence of submersed macrophyte communities in Lake Christina, sediment resuspension was predicted to occur when τ exceeded τ_c.

Additional replicate (10 cores) sediment cores were collected using a Wildco KB sediment corer (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5-cm ID and 50-cm length) for determination of sediment characteristics. The upper 10 cm of sediment was dried at 105 °C to a constant weight for determination of moisture content and sediment density (Håkanson 1977). An additional portion of the sediment sample was combusted at 500 °C for determination of percent organic matter (Håkanson 1977).

During two periods of strong winds (26 August and 9 September) and one period of moderate winds (27 August), the rate of dissolution of gypsum spheres was measured near the lake surface (i.e., 0.15-m depth), at middepth (0.5 m), and near the bottom (0.15 m above the sediment surface) at each station to determine the impacts of a canopy-forming versus a meadow-forming macrophyte community on wind-generated turbulence throughout the vertical water column and shear stress near the sediment-water interface. The spheres, measuring 4.5 cm in diameter, were constructed using a modification of the procedures described by Petticrew and Kalff (1991). A 60:40 mixture of gypsum (as $CaSO_4 \cdot 2H_2O$) and water, respectively, was poured into a rubber mold containing an anchoring bolt and allowed to set up for at least 30 min. The spheres were removed from the mold, dried at 39 to 40 °C for a minimum of 48 hr, and weighed for determination of dry mass. Preweighed spheres were deployed in the lake at each station in triplicate on brackets attached to a PVC pipe that was attached to a post driven into the lake sediment. The spheres were allowed to dissolve in the lake over a 2-hr period and then dried for at least 48 hr to determine loss of gypsum mass (g/h).

The rate of gypsum dissolution was experimentally calibrated with respect to shear stress using the PES. Preliminary experiments indicated that the rate of dissolution was linear with respect to time over a 2-hr period. Thus, gypsum spheres were subjected to different shear stresses over an hourly period in the PES to determine relationships between the rate of dissolution and shear stress. Dissolution rates versus shear stress were determined at 20 °C. These relationships were used to convert rates of gypsum dissolution, measured in the field in different plant beds, to shear stress (Figure 2).

Macrophyte standing crop (g/m^2) in the vicinity of the *Chara* and *M. sibiricum* stations was determined in late August using a 0.56 m^2 quadrat enclosure (i.e., 0.75 m × 0.75 m; Filbin and Barko 1985). Macrophytes within the quadrat were removed using a rake and net. Some roots were inevitably included in each sample. Five randomly selected samples were collected within a 10-m radius of each station. Samples were dried to a constant weight at 70 °C for standing crop determination.

3 Results and Discussion

Turbidity Patterns in Relation to Wind Events, Lake Christina

Since sediment characteristics were similar between the *Chara* and *M. sibiricum* stations, data were combined to compute means. Sediments at these sites exhibited a very high moisture content (85.2 percent ± 4.6), high organic matter content (16.1 percent ± 2.2), and low sediment density (0.20 g/mL ± 0.06), indicative of fine-grained, flocculent sediments (Håkanson 1977). In the laboratory, resuspension of these sediments occurred at low levels of shear stress applied by the PES. TSS concentrations in the overlying water of sediment systems increased markedly as a function of increasing shear stress above 1.4 dynes/cm^2 (Figure 3). From these patterns, we estimated a τ_c of 1.4 dynes/cm^2 for sediments located at the *Chara* and *M. sibiricum* stations in Lake Christina (Figure 3).

During July through September (Figure 4), winds blew most frequently out of the NE and SE wind rose (Table 1). Winds during this period most commonly blew between 5 and 20 km/h from all wind rose (i.e., 61.3 percent of the time). However, winds exceeded 20 km/hr on several occasions (frequency of occurrence of 30 percent) during the study (Table 1 and Figure 4). In particular, wind velocities were 40 km/h on 22 and 26 July, 19 and 22 August, and 19 and 20 September (Figure 4).

Since the *Chara* and *M. sibiricum* stations were adjacent to one another, we estimated one theoretical τ that represented both stations. Theoretical τ, estimated as a function of wind velocity, effective fetch, and wind direction, exceeded τ_c, determined experimentally in the laboratory using intact sediment cores and the PES, 16 percent of the time during the study (Figure 5). Thus, in the absence of submersed macrophytes, resuspension could have potentially occurred during these occasions when $\tau > \tau_c$, resulting in peaks in turbidity in the water column.

During most of the study period, however, turbidity near the sediment interface was < 20 NTU and nearly constant at both stations (Figure 5). In particular, turbidity values did not increase during very high sustained winds that occurred on 3 and 18 August and 9 and 10 September, suggesting that both the

Chara and *M. sibiricum* communities were effectively inhibiting sediment resuspension during periods of high wind velocity. An exception to this pattern occurred on 20 September, when a peak in turbidity > 20 NTU was observed at the *Chara* station in conjunction with very high wind velocities in excess of 45 km/h (Figure 5). An anomalous peak in turbidity, which could not be explained by high winds, occurred on 24 August in the *M. sibiricum*.

Wind Event, 26 August

On 26 August, macrophyte standing crop was 525 g/m^2 (± 73 S.D.) at the *M. sibiricum* station and 245 g/m^2 (± 45 S.D.) at the *Chara* station. *M. sibiricum* stems (~0.95 m in length) were within 0.25 m of the surface of the lake. *Chara* stems were only ~ 0.3-0.4 m in length and, thus, occupied only the near bottom strata of the lake.

During the afternoon of 26 August, winds blew steadily out of the SSW (195 deg) at nearly 30 km/h between ~ 1345 and 1700 hr (Figure 6). The effective fetch for both stations was nearly 2,000 m for this particular wind direction (Figure 7). Under these wind conditions and fetches, we estimated a theoretical τ at both stations of ~ 2.5 dynes/cm^2 in the absence of submersed macrophytes (Figure 8). This theoretical τ was much greater than τ_c estimated for sediments in the laboratory (i.e., 1.4 dynes/cm^2), suggesting the strong potential for sediment resuspension in the absence of submersed macrophytes.

Within the *Chara* bed, shear stress (and the rate of gypsum dissolution) was high near the lake surface as a result of wave activity (Figure 9). In contrast, shear stress was much less near the lake surface within the *M. sibiricum* bed, coincident with the occurrence of plant stems just below the lake surface (Figure 9). High *M. sibiricum* biomass and canopy-forming architecture resulted in dissipation of shear stress to 0 in the lower 0.7 m of the water column of this macrophyte bed. Within the *Chara* bed, shear stress declined with increasing depth as well, but was nearly 1 dyne/cm^2 at the 0.5 m depth. Within the zone of *Chara* growth near the sediment interface, however, shear stress declined to 0. Turbidity near the sediment interface within both macrophyte beds was < 10 NTU during the wind event of 26 August, and did not fluctuate, indicating that sediment resuspension was minimal in both beds on this date (Figure 6).

Wind Event, 27 August

On 27 August, winds blew out of the SSW (199 deg) during 1130 through 1600 hr at only about 15 to 20 km/h (Figure 10). Although the effective fetch for this wind direction was substantial (2,200 m; Figure 11) for the *M. sibiricum* and *Chara* stations, the lower wind speeds, relative to those observed during the afternoon of 26 August, resulted in an estimated theoretical τ of only about 1 dyne/cm^2 at these stations (Figure 12). Since theoretical τ was < τ_c

(1.4 dynes/cm^2), the potential for sediment resuspension in the absence of submersed macrophytes was negligible.

Gypsum dissolution and shear stress within the *M. sibiricum* and *Chara* beds between 1100 and 1300 hr on 27 August were greatest near the surface of the lake, and declined to zero at depths 0.5 m (Figure 13). Near the lake surface, shear stress was much lower at both stations on 27 August than on 26 August, coincident with much lower wind speeds on the former date. Shear stress was also greater near the lake surface in the *Chara* bed versus the *M. sibiricum* bed on 27 August. This pattern was similar to patterns observed on 26 August, suggesting that differences in the distribution of biomass within the water column (i.e., canopy- versus meadow-forming architecture) were having differing impacts on wind-generated wave activity and shear stress.

Within both macrophyte beds, turbidity near the sediment interface was low, indicating minimal sediment resuspension on the afternoon of 27 August (Figure 10). An anomalous peak in turbidity occurred at 1045 hr which did not correspond to peaks in wind and probably did not represent a resuspension event.

Wind Event, 9 September

On 9 September, *M. sibiricum* stems had reached the surface of the lake. Biomass (undetermined) was assumed to be equal to or greater than values determined on 26 August. Winds blowing out of the south fluctuated between 35 and 45 km/h between 1100 and 1700 hr (Figure 14). The effective fetch for both stations during this period was ~ 1,600 m (Figure 15), resulting in a theoretical τ at both station of ~ 3.0 dynes/cm^2 (Figure 16). Theoretical τ was well above the τ_c of 1.4 dynes/cm^2 for sediments in the lake.

As on 26 August, shear stress within the *Chara* bed was greatest at the lake surface during the morning and afternoon of 9 September, as a result of wind-generated wave activity (Figures 17 and 18). At the 0.5-m depth in this macrophyte bed, shear stress dissipated markedly to ~ 1 dyne/cm^2. Within the zone of *Chara* growth in the lower stratum of the water column, shear stress levels were ~0.2-0.3 dynes/cm^2, which was well below τ_c. In contrast, shear stress was near zero throughout the water column within the *M. sibiricum* bed (Figures 17 and 18). Although turbidity was not monitored in the *M. sibiricum* bed due to an instrument malfunction, turbidity within the *Chara* bed was low throughout the morning and afternoon of 9 September, indicating minimal resuspension (Figure 14).

4 Conclusions

Implications of Aquatic Macrophyte Management in Shallow Systems

The critical shear stress of sediments in Lake Christina was relatively low and fell within the range observed for fine-grained cohesive sediments (Lick, Xu, and McNeil 1995). These characteristics, coupled with large effective fetches and shallow depths in most regions in the lake, provided a backdrop for sediment resuspension under conditions of high wind velocity in the absence of aquatic macrophytes. In particular, theoretical τ was greater than τ_c 16 percent of the time for both stations during the study period, suggesting the potential for resuspension. However, resuspension was only observed on 1 day (20 September) during the study period at the *Chara* station when winds and theoretical τ exceeded 45 km/h and 4 dynes/cm^2, respectively. We attribute the lack of resuspension in the lake during most periods of high winds to the occurrence of submersed macrophyte biomass, which stabilized the sedimentary environment. Others (Fonseca et al. 1982; Gregg and Rose 1982; Eckman, Duggins, and Sewell 1989; Dieter 1990; James and Barko 1994) have shown that submersed and emergent macrophytes can play an important role in reducing wind-generated sediment resuspension by dampening wave activity and redirecting currents.

Effects of Canopy- and Meadow-Forming Beds

It appears that both the canopy-forming *M. sibiricum* and meadow-forming *Chara* beds were equally effective in reducing wave-generated shear stress near the sediment interface, as sediment resuspension was minor in both beds even during strong wind events such as on 9 September. One important variation between the two beds was the observed difference in the dissipation of shear stress (measured as gypsum dissolution) throughout the water column. Within the meadow-forming *Chara* bed, shear stress and, thus, wave activity were high in the upper water column, which coincided with the lack of *Chara* biomass within these water strata. Nevertheless, shear stress declined to near zero above the sediment interface within the zone of *Chara* growth. Similarly, Koch (1996) found the generation of high-frequency turbulent energy above meadow-forming

seagrass, *Thalassia testudinum,* and dramatic declines in flow to near zero within the vegetation structure, particularly for beds exhibiting epiphytic cover over the macrophytes.

Shear stress and wave activity were much less throughout the water column within the canopy-forming *M. sibiricum* bed, compared to patterns observed within the *Chara* bed. These observations were consistent with the occurrence of biomass within the upper strata, near the lake's surface, which dampened wave energy. In addition, the position of the *M. sibiricum* canopy in the water column also had an important impact on shear stress dissipation. Shear stress within this bed was higher in the upper water strata on 26 August when the canopy was below the lake surface versus 9 September when the canopy was at the lake surface.

The roles played by macrophytes in reducing shear stress and sediment resuspension have important implications for the restoration and management of shallow aquatic systems. In particular, the establishment of stands of meadow-forming macrophyte species such as *Chara* or *Vallisneria* may provide for both sediment stability from resuspension and open surface water for boating and other recreational activities. More information is needed on the impacts of architecturally different macrophyte communities on wave characteristics to improve water quality in shallow water systems with attention to the role of macrophyte communities in stabilizing the sedimentary environment.

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Table 1
Frequency (%) of occurrence of wind speeds blowing from the northeast (NE), southeast (SE), southwest (SW), and northwest (NW) wind rose during late July through September 1998

Wind Speed, km/h	Wind Direction				
	NE	SE	SW	NW	Total
< 5	4.3	0.8	0.9	2.0	8.1
5 - 10	10.0	3.6	4.6	3.8	22.0
10 -15	6.1	5.8	4.7	4.6	21.1
15 - 20	4.2	6.4	4.0	3.8	18.3
20 - 25	3.6	4.9	2.9	2.8	14.1
25 - 30	1.7	2.4	2.8	1.6	8.4
30 - 35	0.1	2.3	1.4	1.0	4.8
> 35	0.0	1.1	0.9	1.0	3.1
Total	30.0	27.4	22.1	20.5	100.0

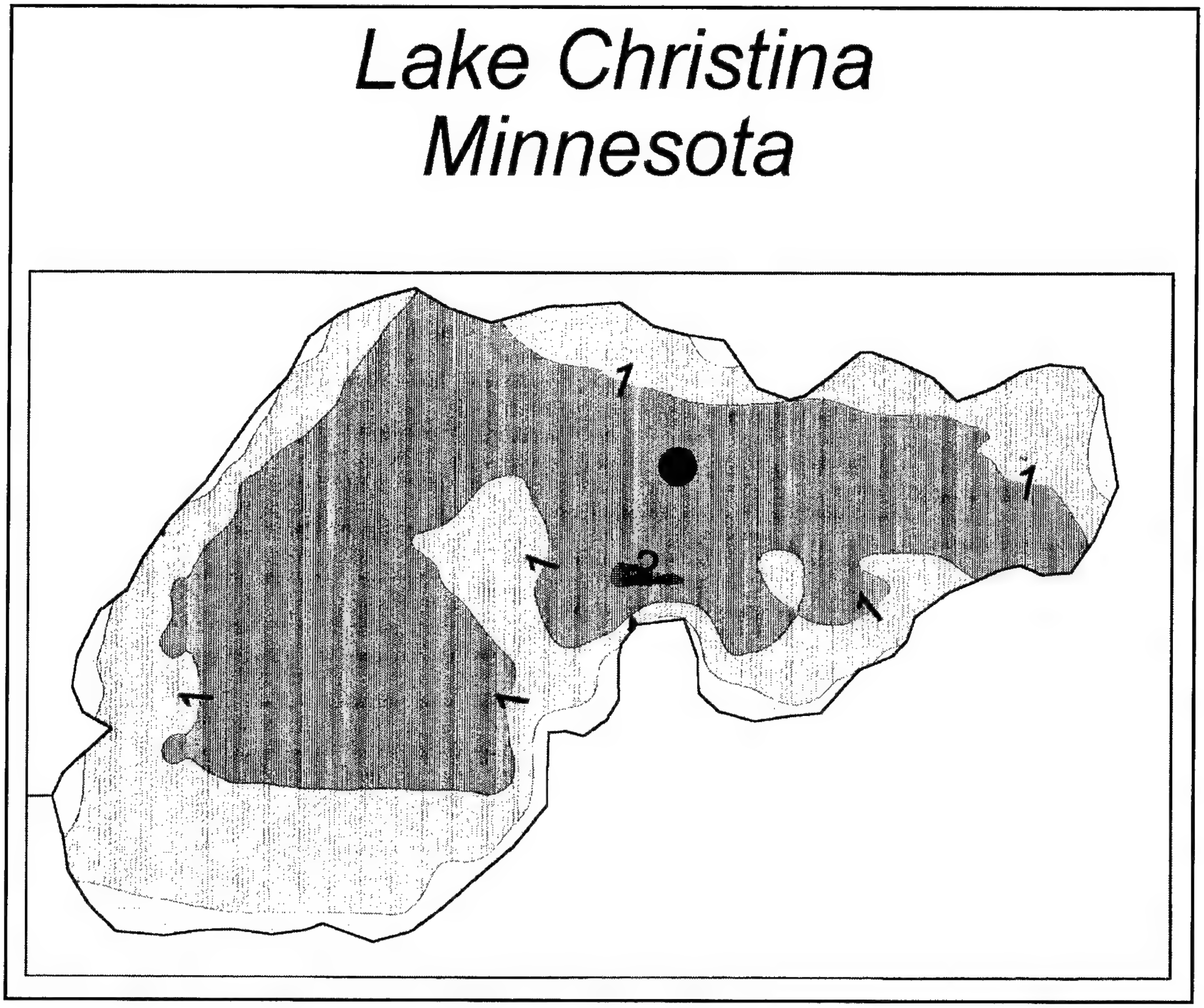

Figure 1. Bathymetric map of Lake Christina showing the location (solid circle) of the adjacent *Chara* and *Myriophyllum sibiricum* beds. Depth contours are in meters

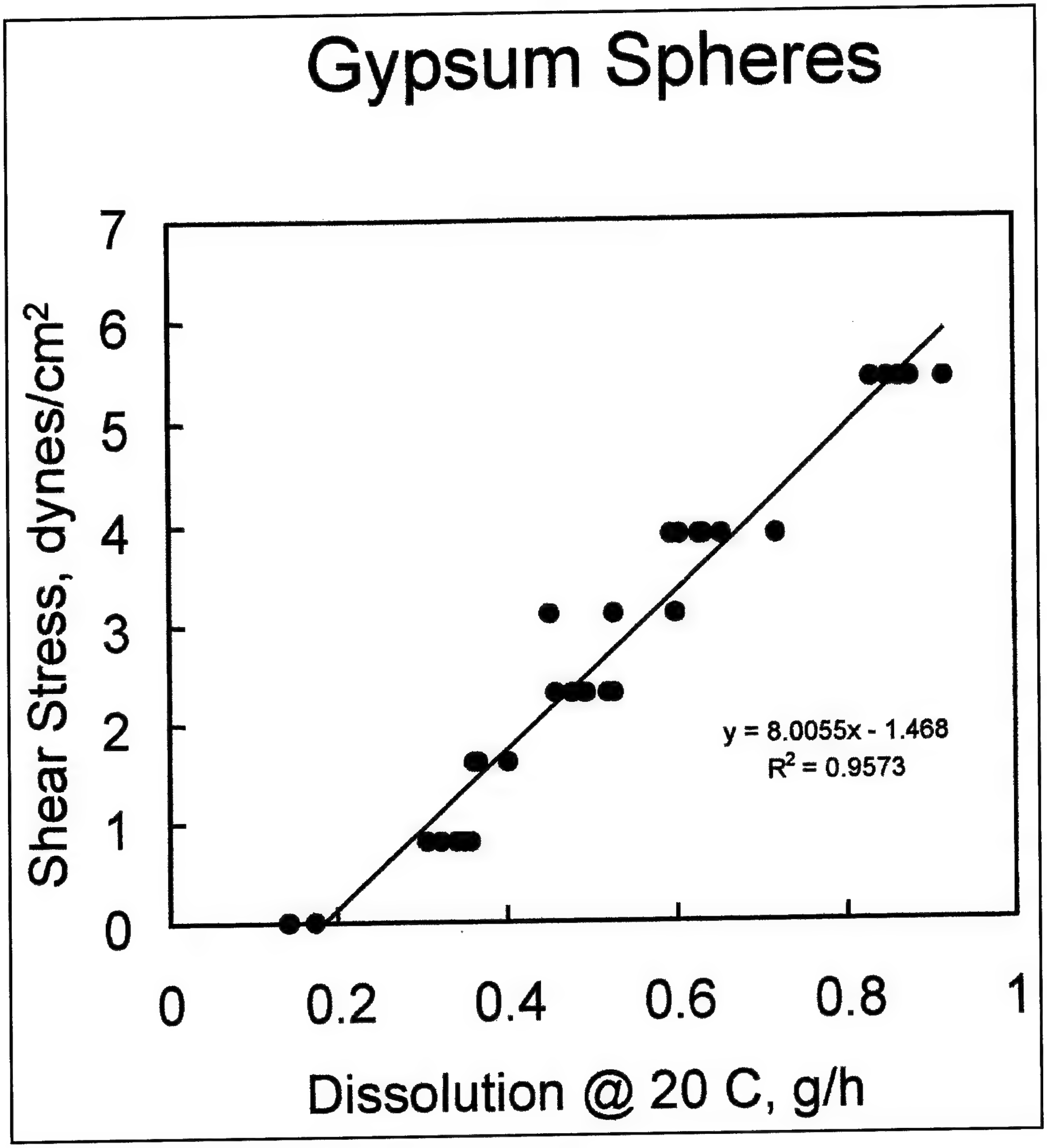

Figure 2. Relationship between gypsum sphere dissolution at 20 °C and shear stress generated experimentally in the laboratory using a particle entrainment simulator

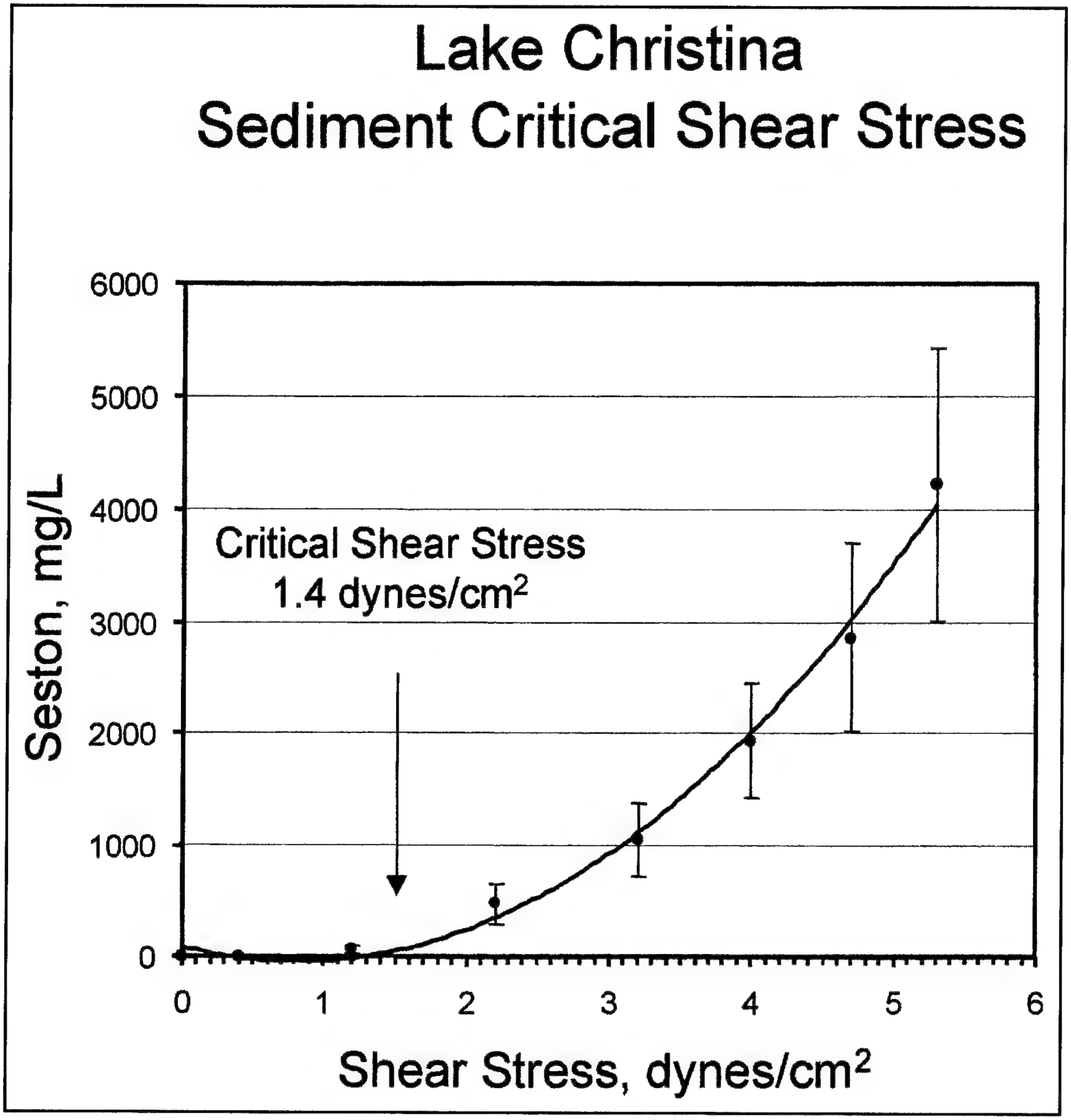

Figure 3. Variations in mean (± 1 S.D.) suspended seston concentration as a function of shear stress for intact sediment cores collected at the *Chara* and *Myriophyllum sibiricum* beds in Lake Christina. Shear stress was generated experimentally in the laboratory using a particle entrainment simulator

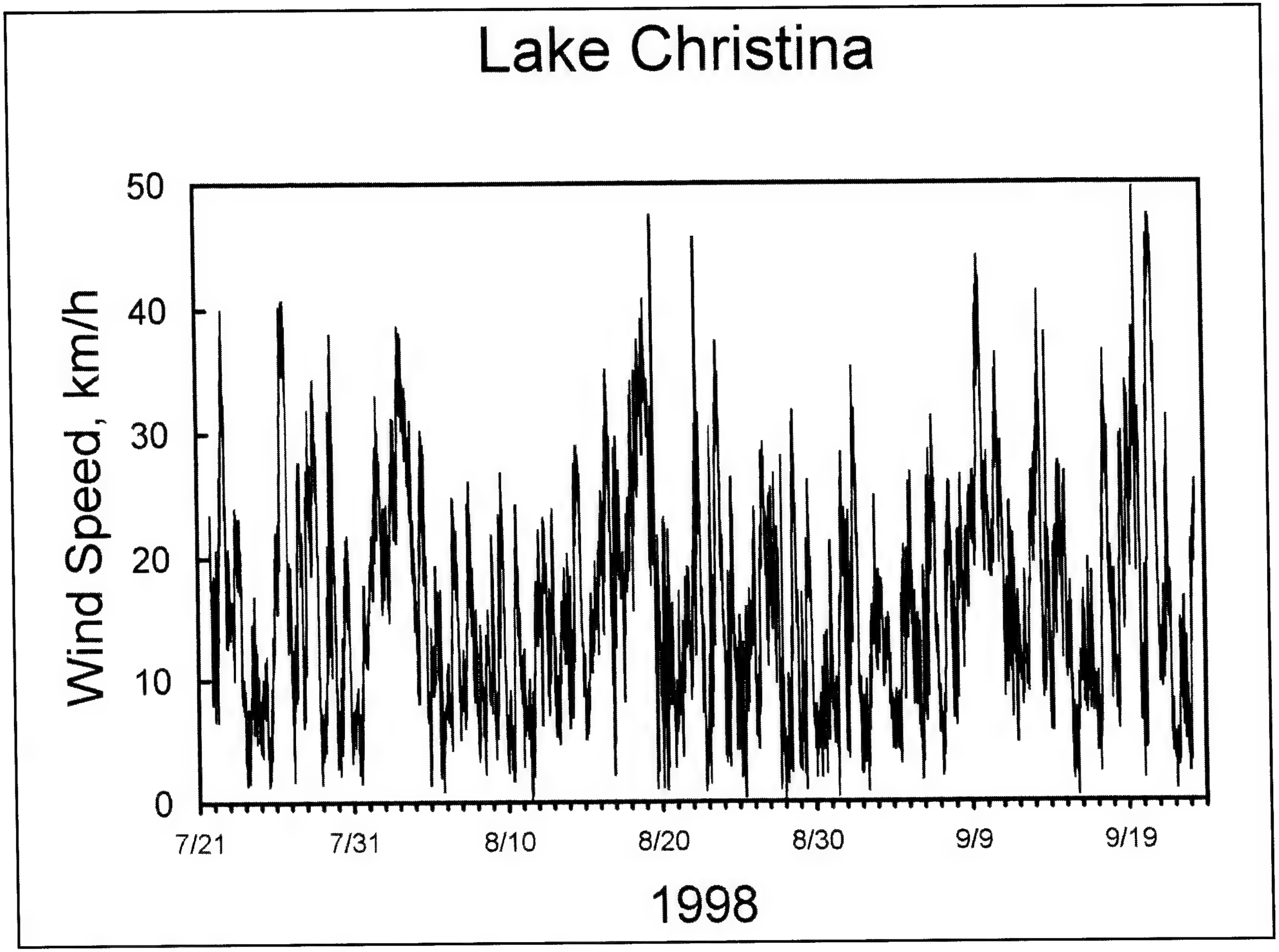

Figure 4. Variations in wind speed in Lake Christina between late July and September 1998

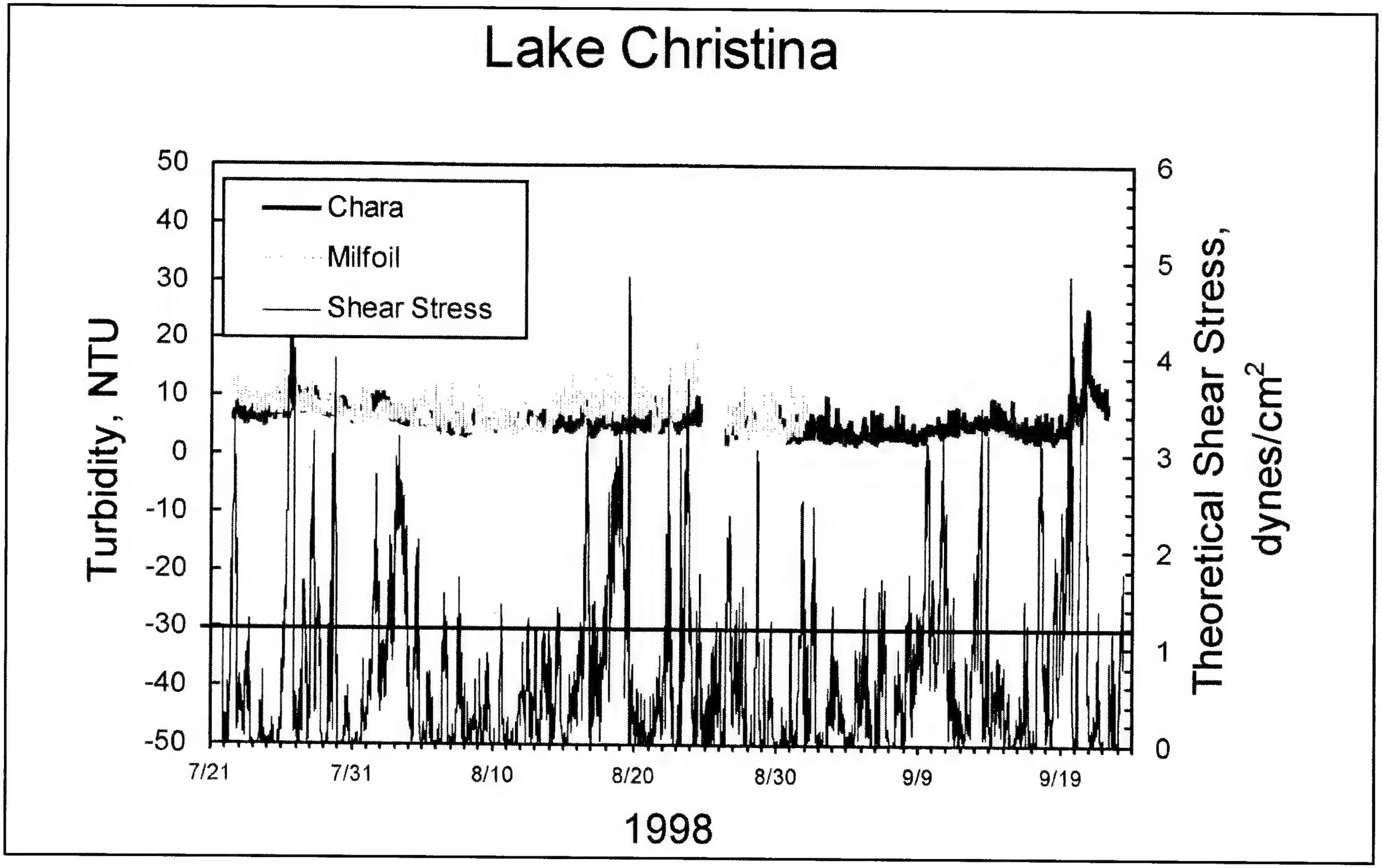

Figure 5. Variations in *in situ* turbidity, monitored in the *Chara* and *Myriophyllum sibiricum* beds, and theoretical shear shear, calculated using wind information and effective fetch. Theoretical shear stress does not account for impacts that macrophytes have on dampening wave activity. The horizontal black line represents the critical shear stress of the sediments in Lake Christina, measured experimentally in the laboratory using a particle entrainment simulator

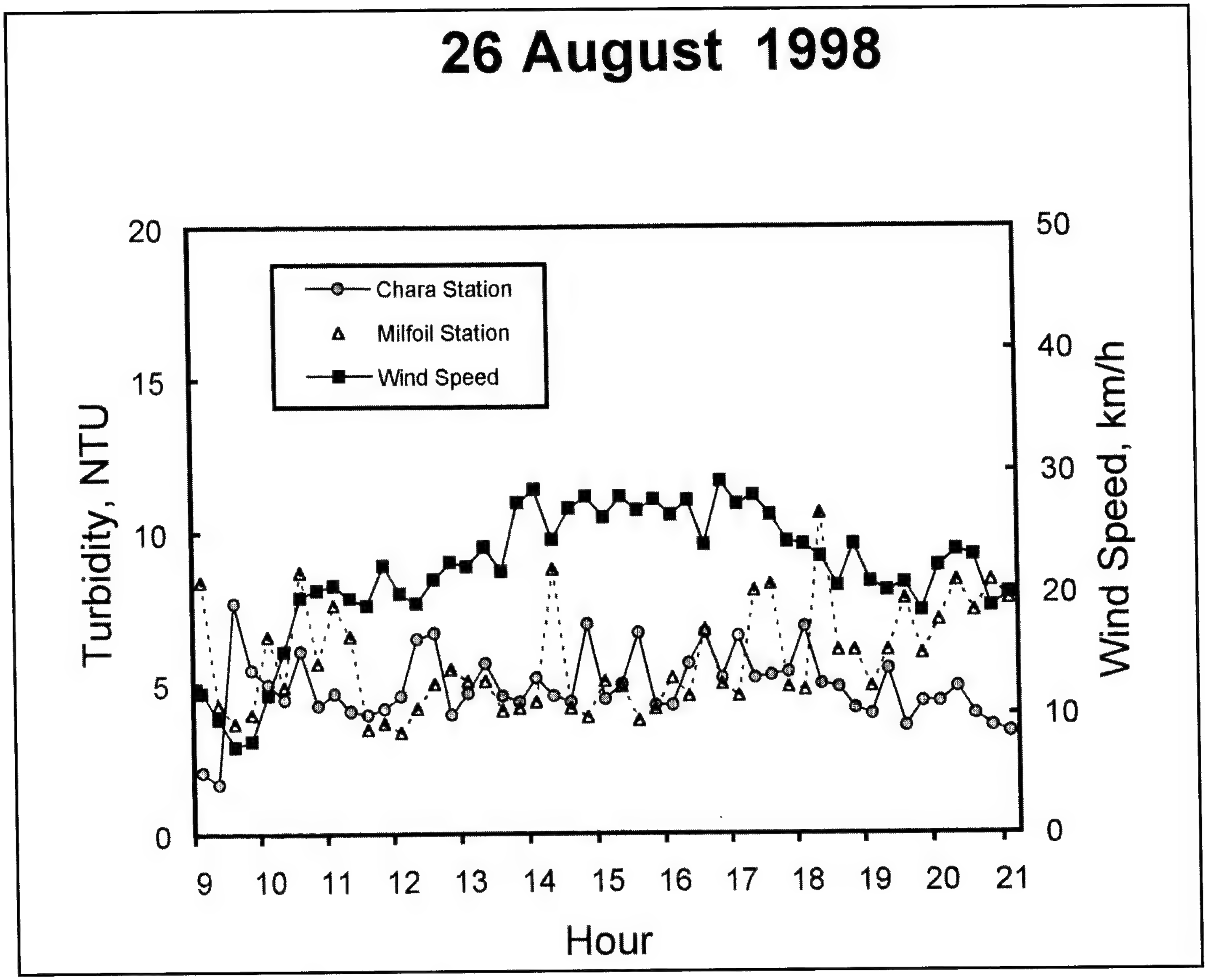

Figure 6. Variations in wind speed and *in situ* turbidity in the *Chara* and *Myriophyllum sibiricum* beds on 26 August 1998

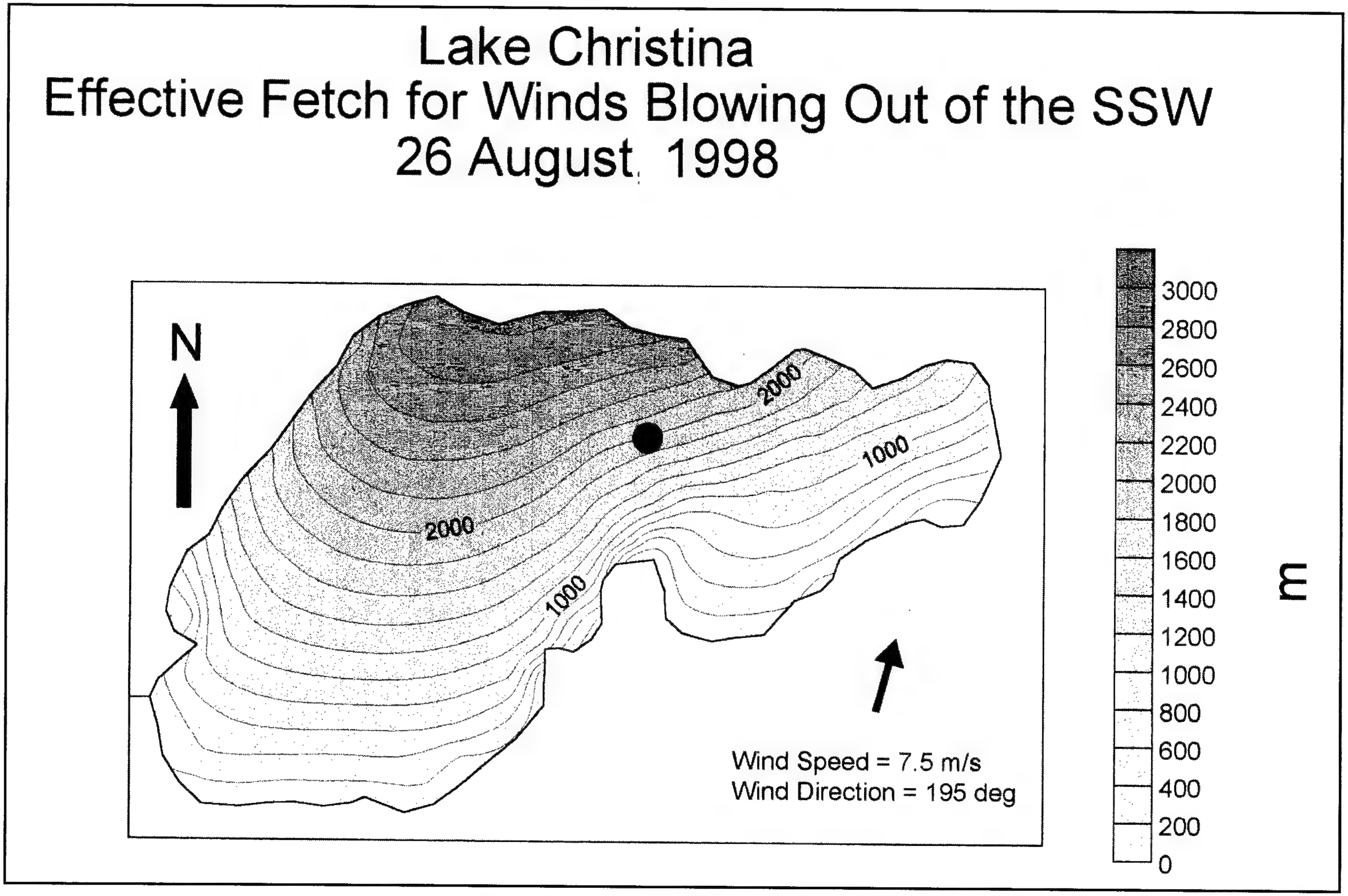

Figure 7. Contour plot of effective fetches in Lake Christina for winds blowing out of the south-southwest (SSW) at 7.5 m/s on 26 August 1998. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

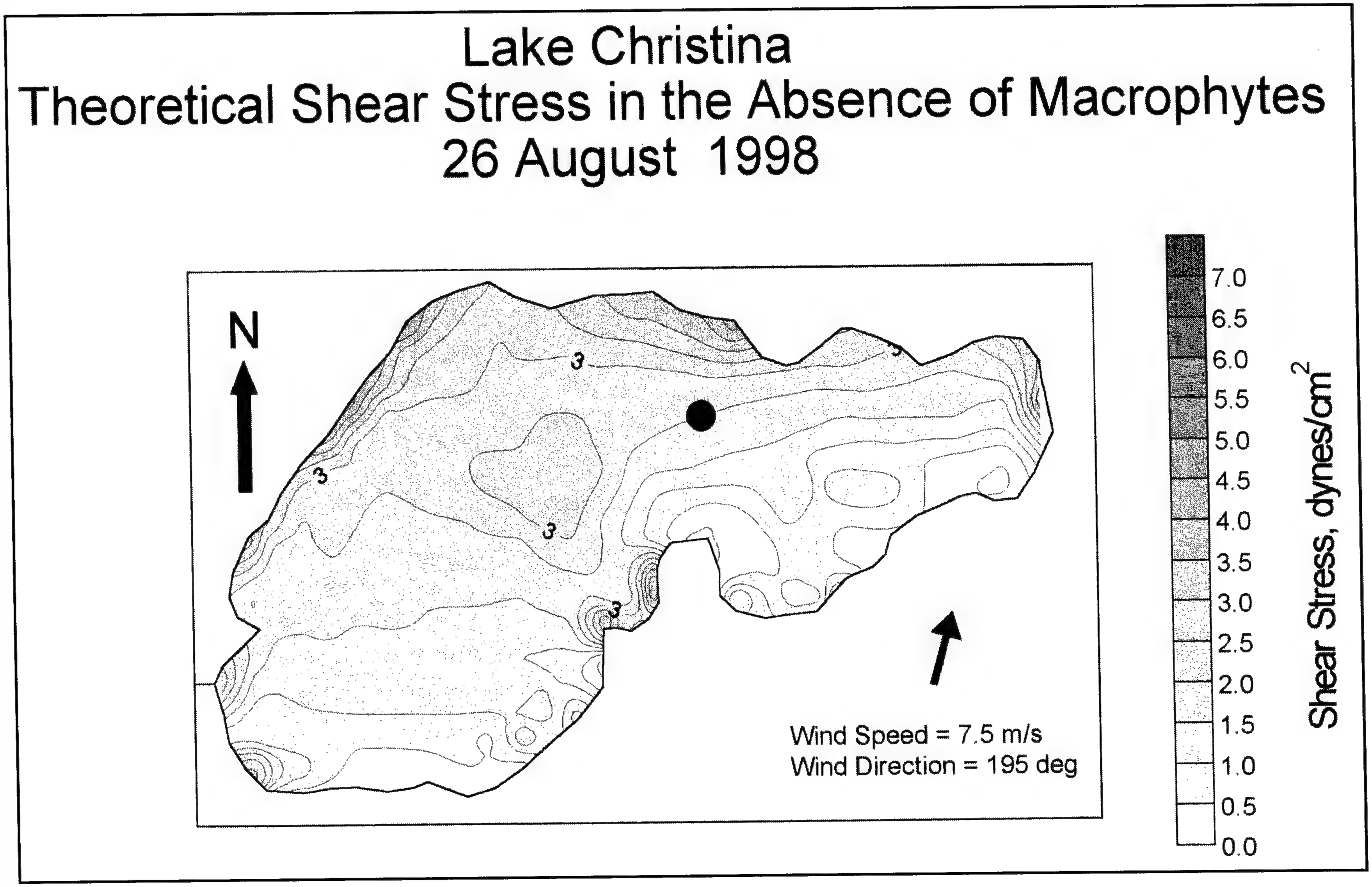

Figure 8. Contour plot of theoretical shear stress in Lake Christina for winds blowing out of the south-southwest (SSW) at 7.5 m/s on 26 August 1998. The theoretcial shear stress does not account for impacts that macrophytes have on dampening wave activity. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

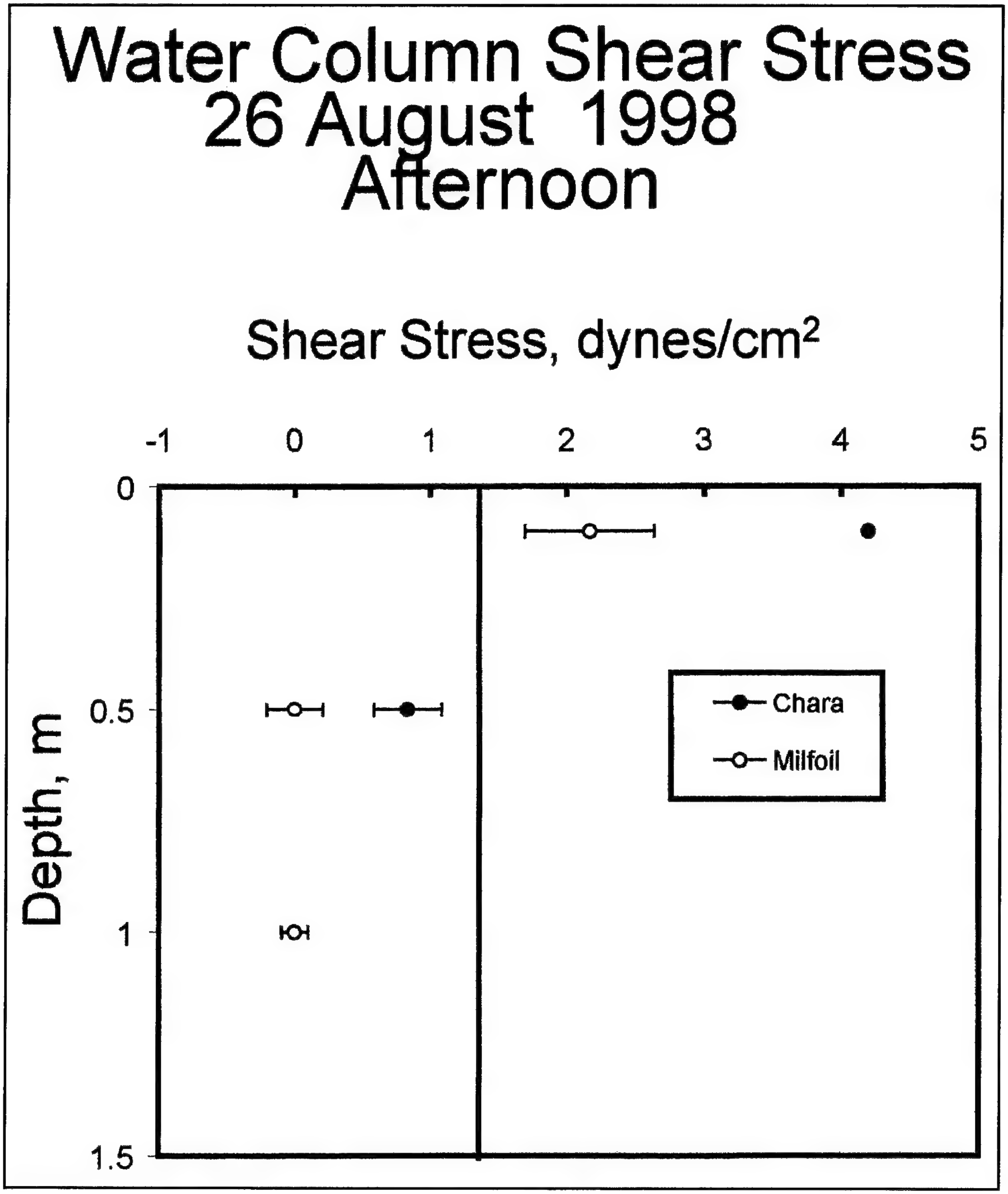

Figure 9. Depth-related variations in shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the afternoon (i.e., 1430 to 1645 hr) on 26 August 1998. The vertical black line represents the critical shear stress of the sediments in Lake Christina, measured experimentally in the laboratory using a particle entrainment simulator

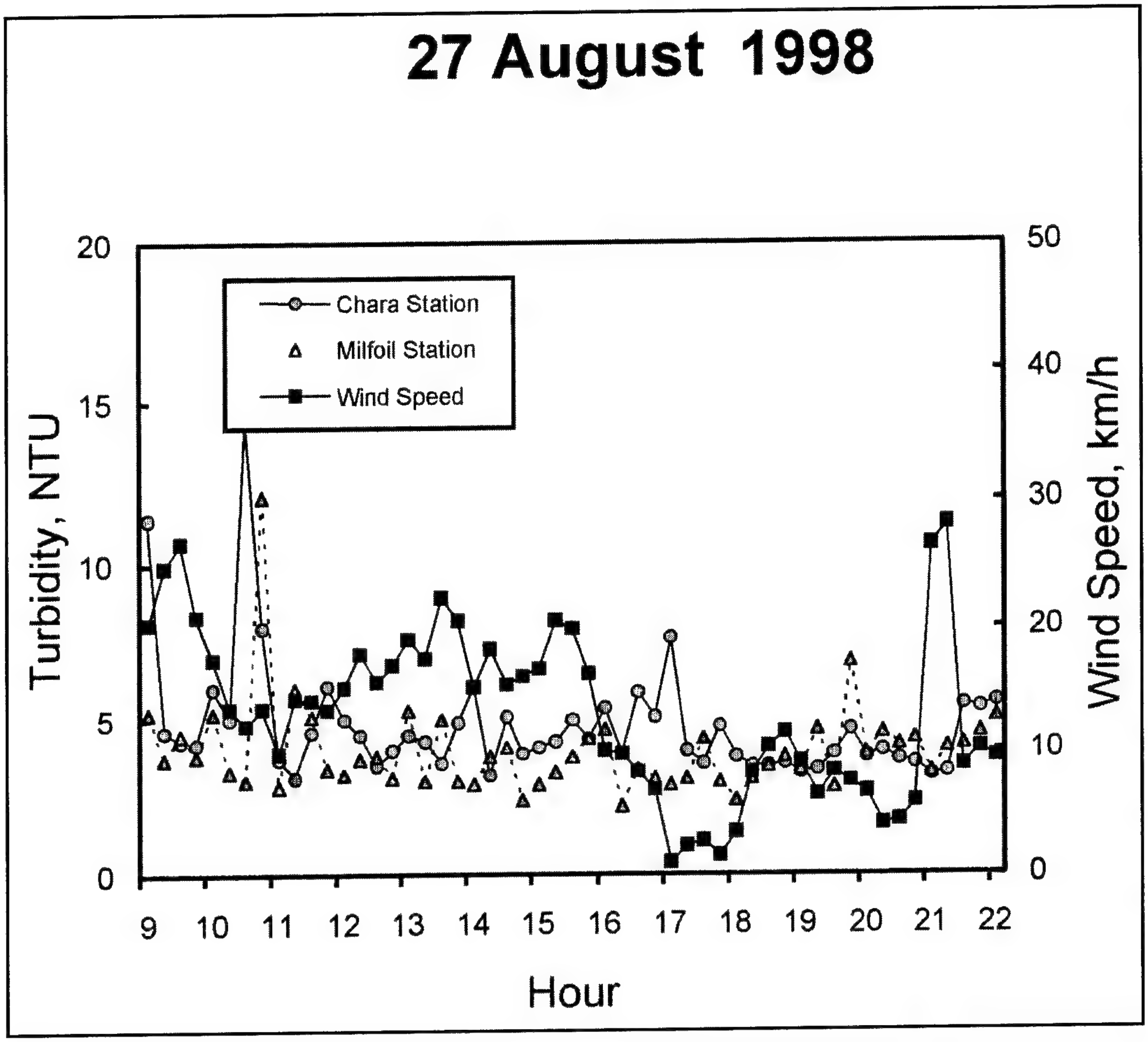

Figure 10. Variations in wind speed and *in situ* turbidity in the *Chara* and *Myriophyllum sibiricum* beds on 27 August 1998

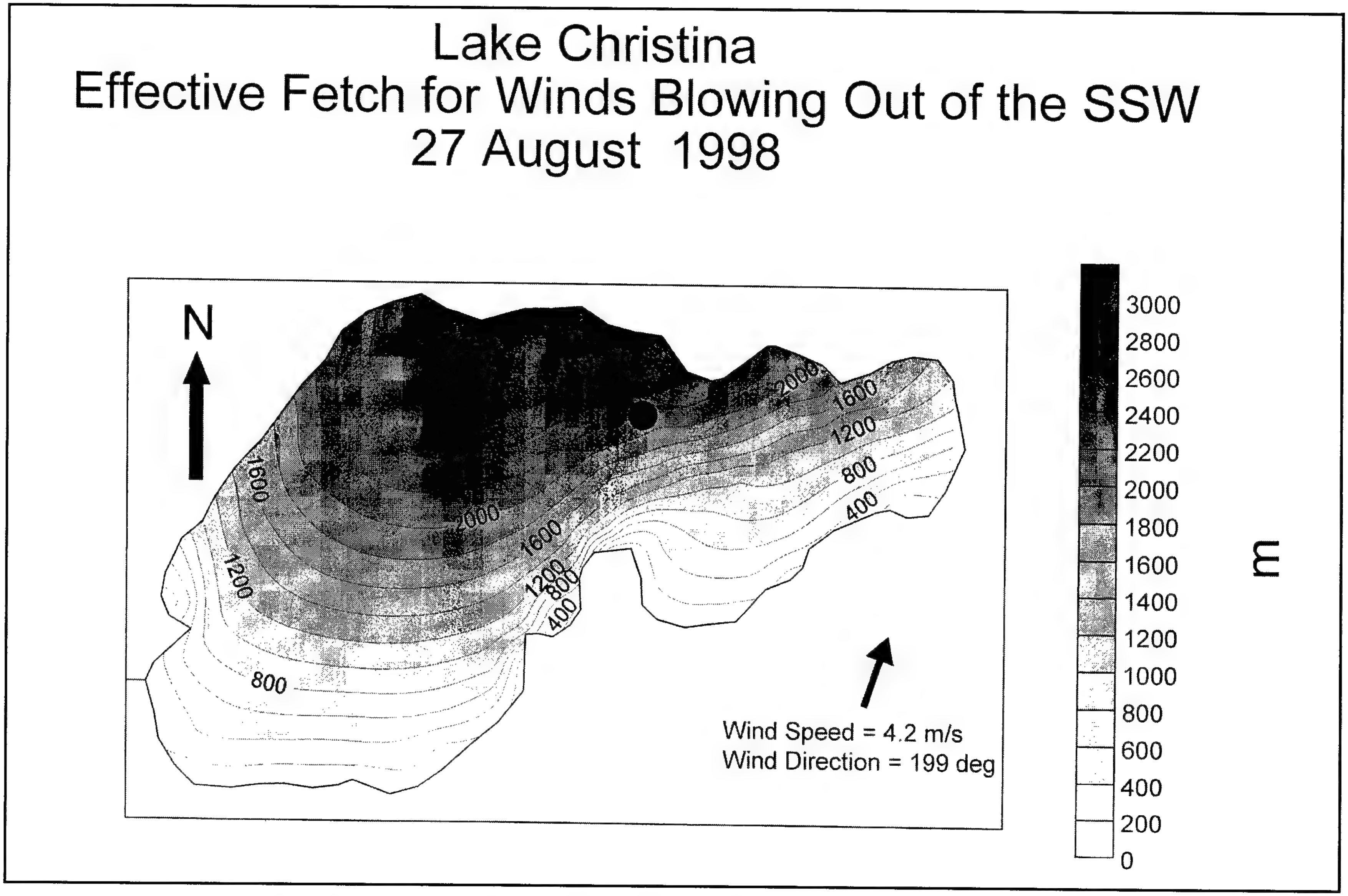

Figure 11. Contour plot of effective fetches in Lake Christina for winds blowing out of the south-southwest (SSW) at 4.2 m/s on 27 August 1998. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

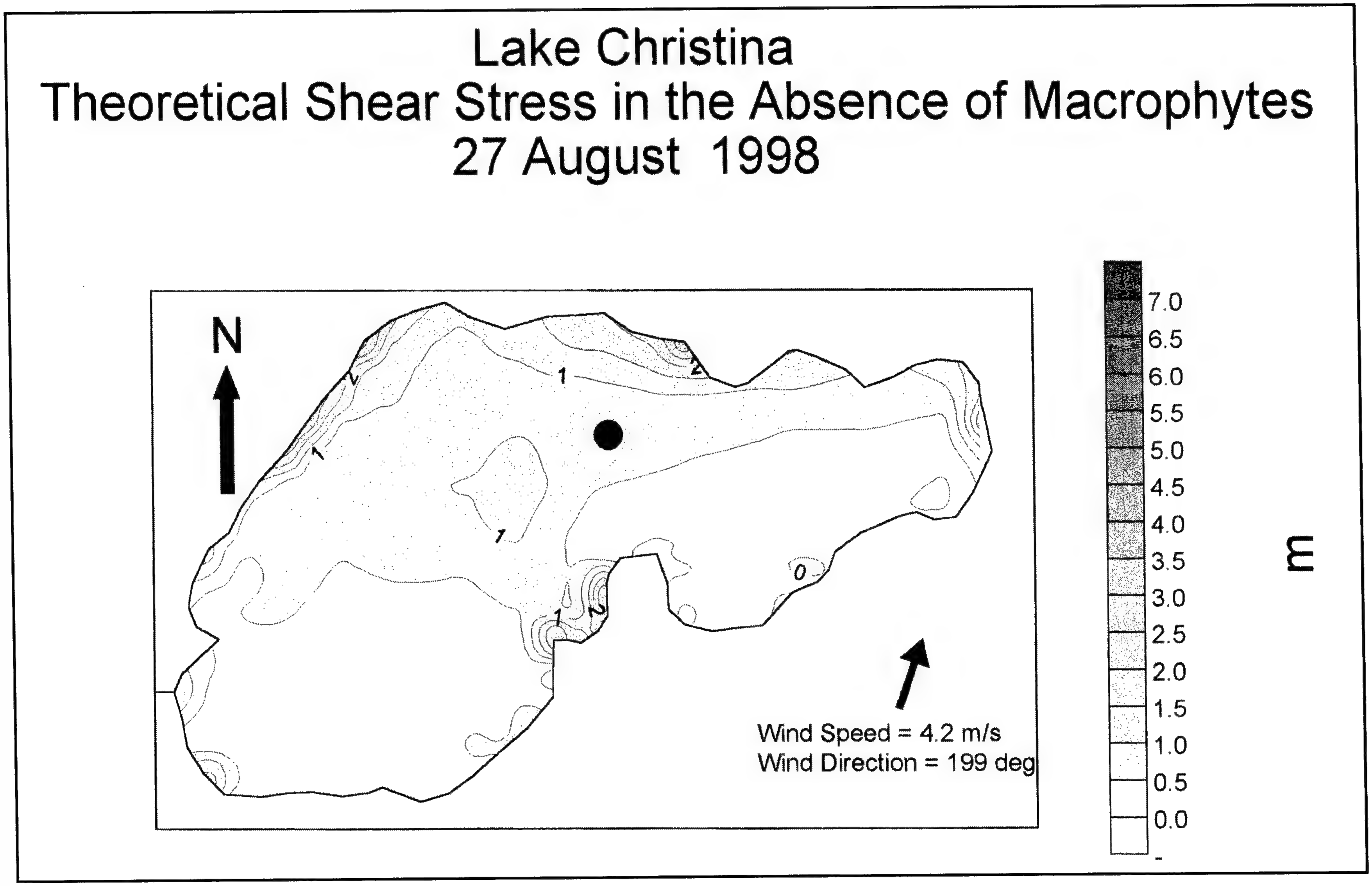

Figure 12. Contour plot of theoretical shear stress in Lake Christina for winds blowing out of the south-southwest (SSW) at 4.2 m/s on 27 August 1998. The theoretical shear stress does not account for impacts that macrophytes have on dampening wave activity. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

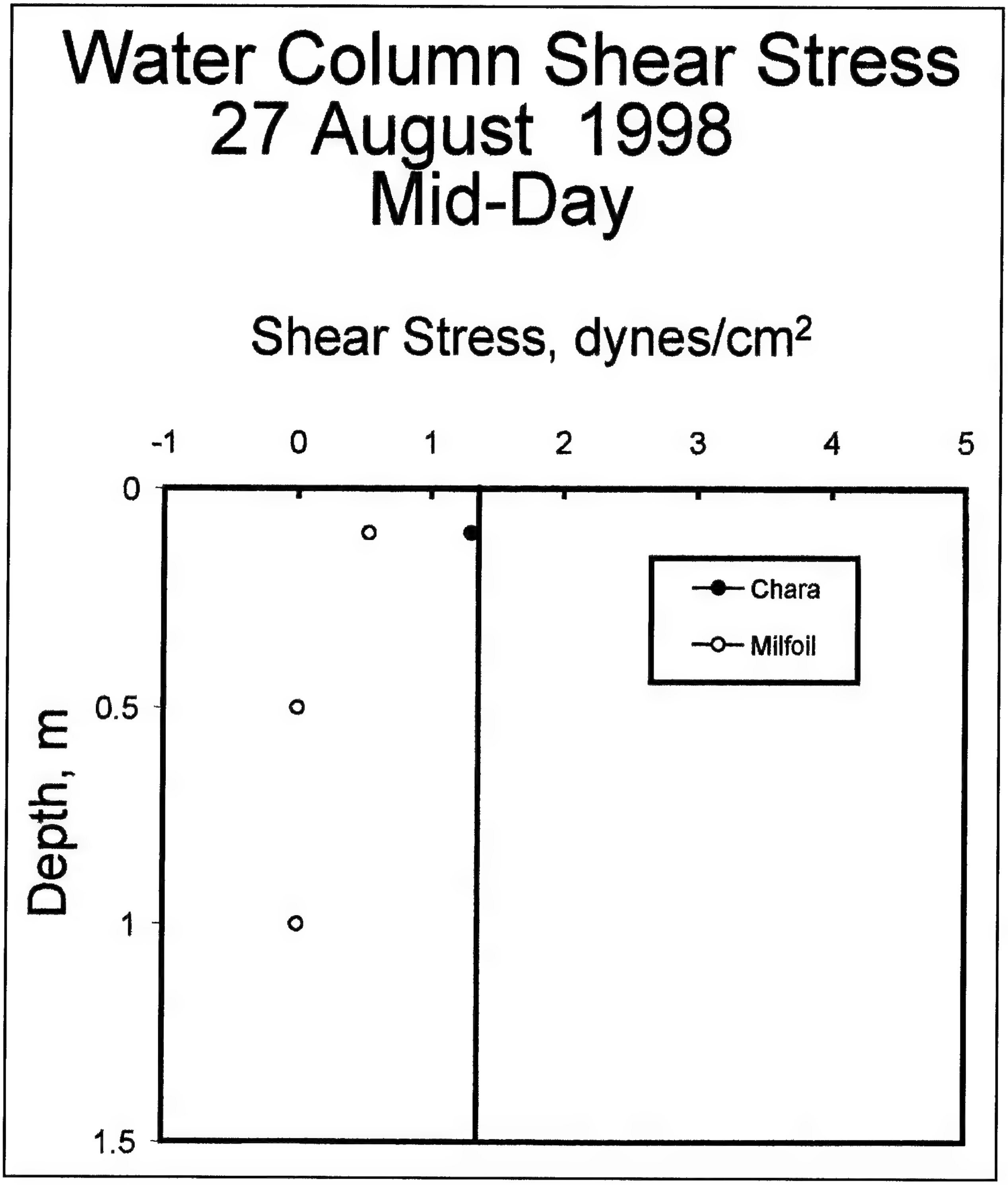

Figure 13. Depth-related variations in shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the afternoon (i.e., 1100 to 0130 hr) on 27 August 1998. The vertical black line represents the critical shear stress of the sediments in Lake Christina, measured experimentally in the laboratory using a particle entrainment simulator

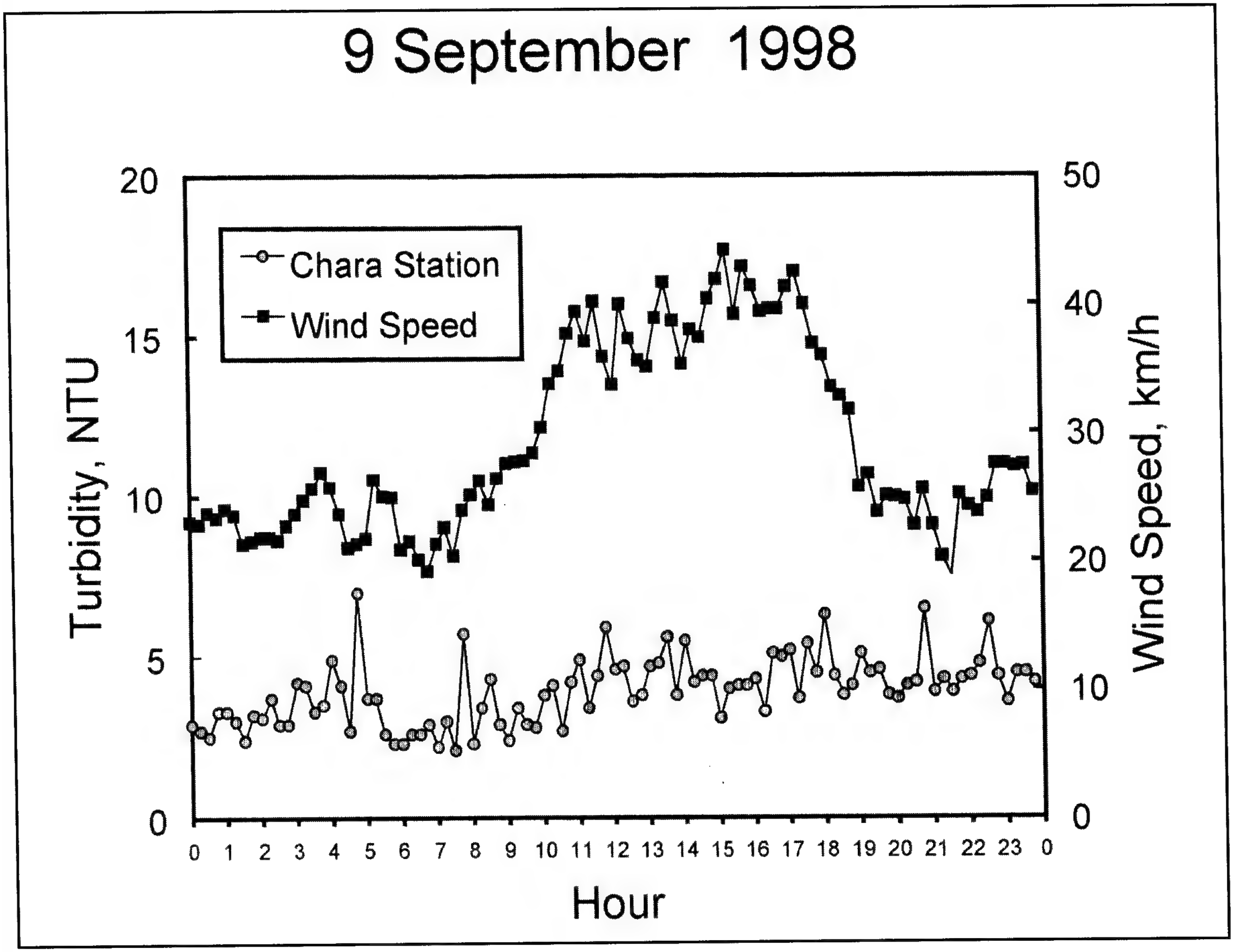

Figure 14. Variations in wind speed and *in situ* turbidity in the *Chara* and *Myriophyllum sibiricum* beds on 9 September 1998

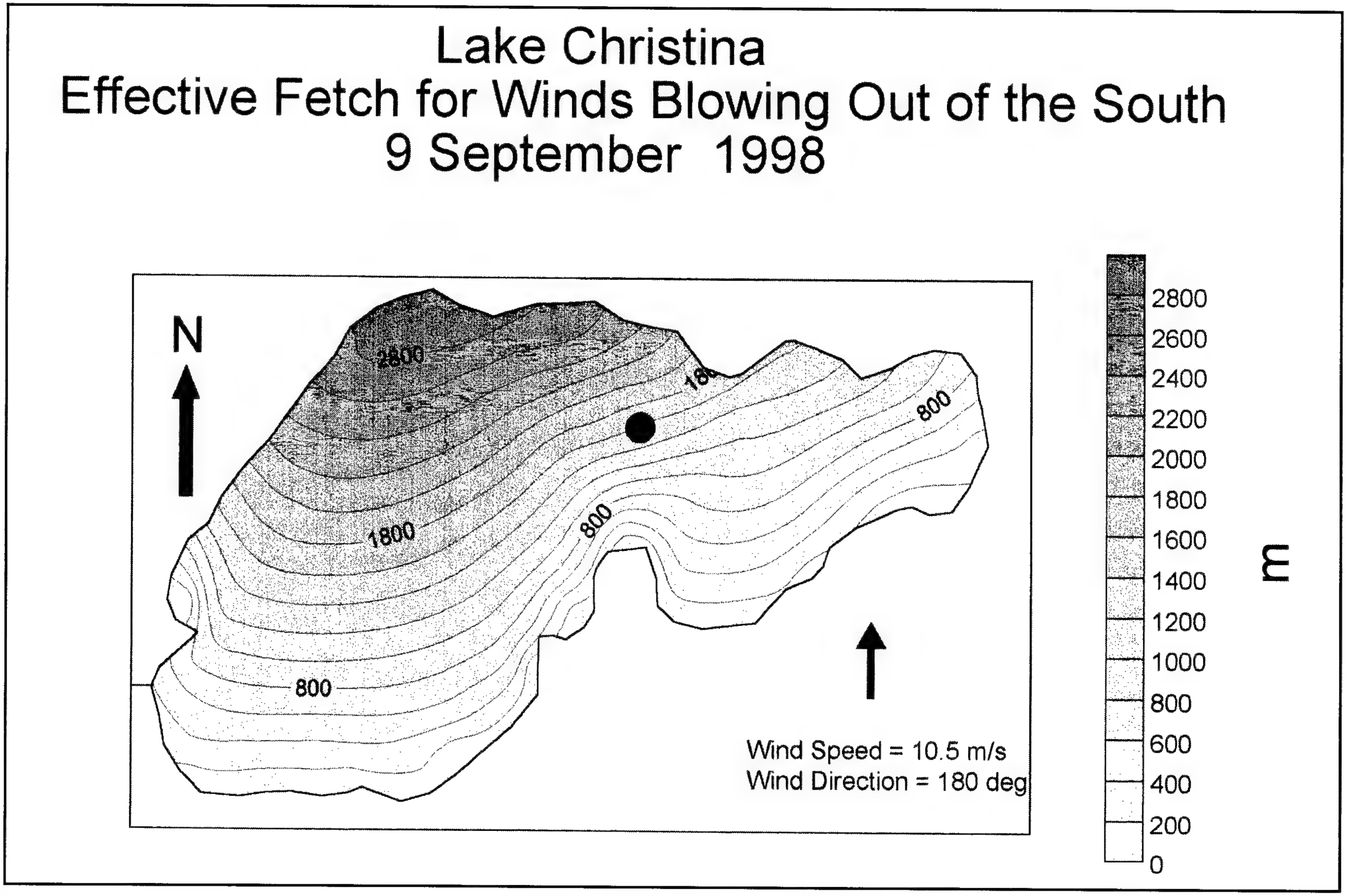

Figure 15. Contour plot of effective fetches in Lake Christina for winds blowing out of the south (S) at 10.5 m/s on 9 September 1998. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

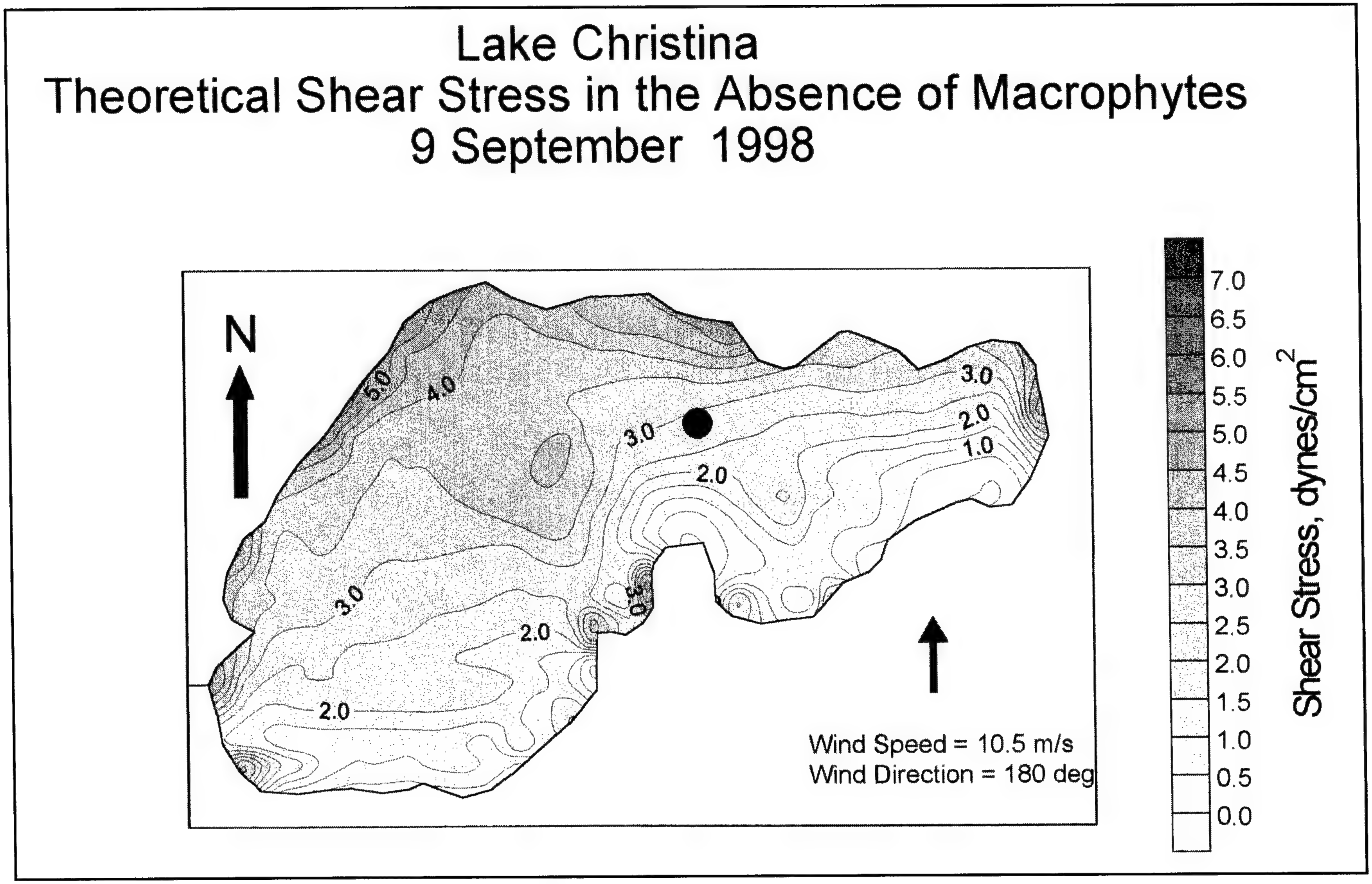

Figure 16. Contour plot of theoretical shear stress in Lake Christina for winds blowing out of the south (S) at 10.5 m/s on 9 September 1998. The theoretical shear stress does not account for impacts that macrophytes have on dampening wave activity. The solid circle represents the location of the adjacent *Chara* and *Myriophyllum sibiricum* beds

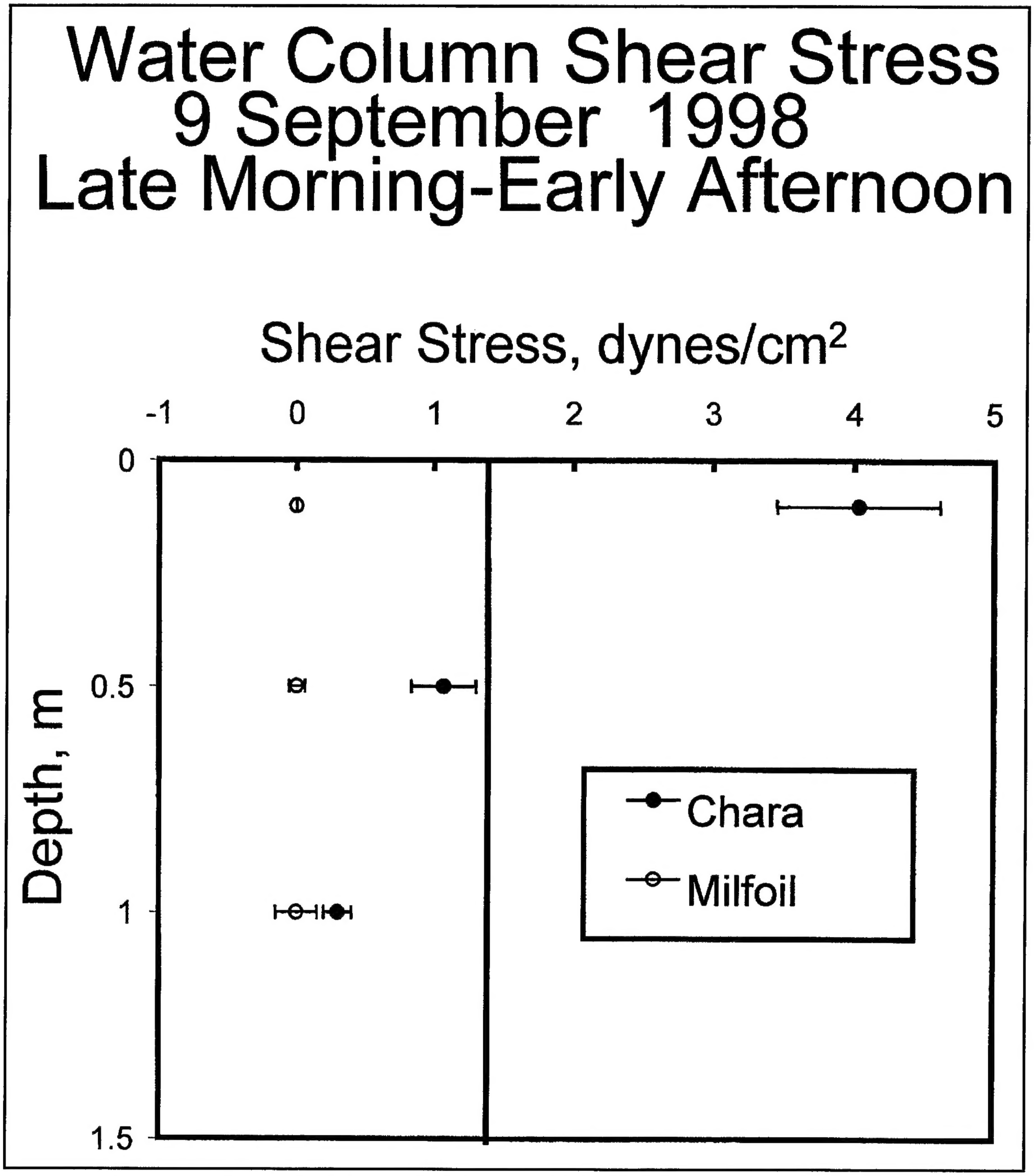

Figure 17. Depth-related variations in shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the late morning to early afternoon (i.e., 1145 to 1345 hr) on 9 September 1998. The vertical black line represents the critical shear stress of the sediments in Lake Christina, measured experimentally in the laboratory using a particle entrainment simulator

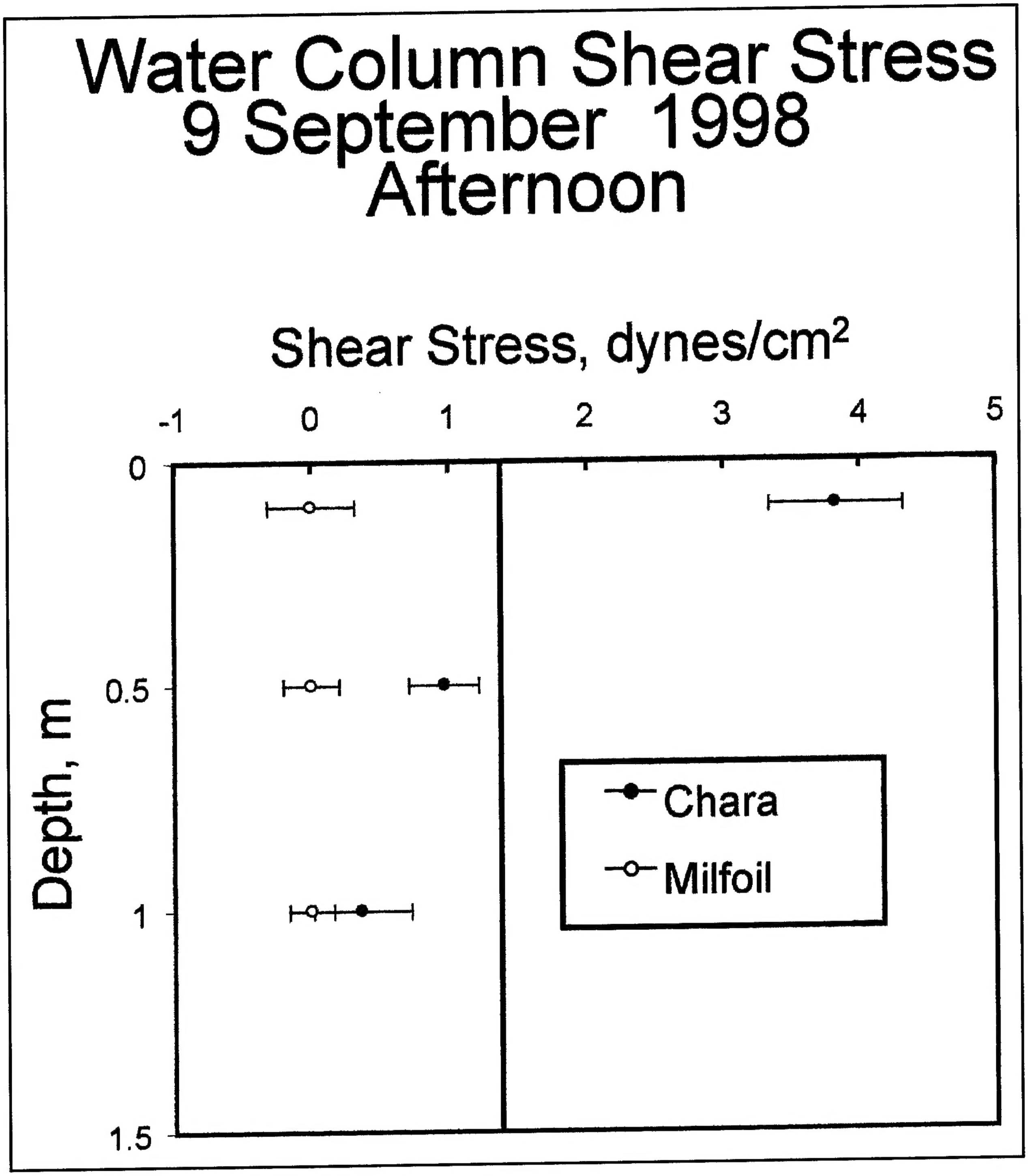

Figure 18. Depth-related variations in shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the afternoon (i.e., 1345 to 1545 hr) on 9 September 1998. The vertical black line represents the critical shear stress of the sediments in Lake Christina, measured experimentally in the laboratory using a particle entrainment simulator

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

We examined the impacts of macrophyte beds dominated by a canopy-forming (*Myriophyllum sibiricum*) and a meadow-forming (*Chara*) species on shear stress near the sediment interface and resuspension in the large (1,620 ha) and shallow (1.25 m) Lake Cristina, Minnesota. The surface sediments in the vicinity of an adjacent *M. sibiricum* and *Chara* station, located in the northern region of the lake, exhibited a high moisture content (85 percent), low sediment density (0.2 g/mL), and high organic matter content (16 percent), indicative of fine-grained, flocculent sediment. The critical shear stress (τ_c) of these sediments, measured experimentally in the laboratory using a particle entrainment simulator, was low (1.4 dynes/cm2) and indicated a strong potential for resuspension at moderate wind speeds in the absence of submersed macrophytes. Between late July and September 1998, theoretical shear stress (τ), calculated using wind data, and wave theory (i.e., assuming no macrophyte biomass in the lake to obstruct wave activity) exceeded the experimentally derived sediment critical shear stress 16 percent of the time. However, *in situ* turbidity at both the canopy-forming *M. sibiricum* and meadow-forming *Chara* station was low and rarely increased when τ exceeded τ_c, indicating that both macrophyte beds reduced sediment resuspension in the lake. *In situ* shear stress, measured using calibrated gypsum spheres, was high near the open water lake surface during periods of high winds.
(Continued)

15. SUBJECT TERMS
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14. ABSTRACT (Concluded)

However, it declined to near zero within the zone of *Chara* growth (30 to 40 cm) just above the sediment interface and was low both near the water surface and near the sediment interface in the canopy-forming *M. sibiricum* bed. Our results indicate that both canopy-forming and meadow-forming macrophyte communities can reduce sediment resuspension by dampening wave activity and shear stresses required to resuspend sediments.